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A summary of research performed by 12 faculty members of the Dept. of Earth and Planetary Sciences and Meteorology at MIT, funded by ONR contract N00014-75-C-0291.

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Final Report on Contract N00014-75-C-0291

To: Office of Naval Research
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and Meteorology
Massachusetts Institute of Technology
Cambridge, Mass.

Period of Performance: October 1, 1974 - December 31, 1979

Funding was received from the Office of Naval Research under Contract N00014-75-C-0291 during the period October 1, 1974 through December 31, 1979.

Twelve faculty and 2 research staff members of the Departments of Earth and Planetary Science and Meteorology participated:

John B. Southard - Project XIII

John M. Edmond - Project XVII-A and XXIX

John G. Sclater and Barry Parsons - Projects XVIII-A, XXVIII

Tanya Atwater - Project XVIII-B

Carl Wunsch - Projects XXI and XXII

Eric Mollo-Christensen - Project XXV

Stanley R. Hart - Project XXVI

Henry M. Stommel and Lloyd Regier - Project XXIX

Sean C. Solomon - Project XXX

Giselher Güst - Project XXXII

Charles C. Eriksen - Project XXXIII

Edward A. Boyle - Project XXXIV

Following is a brief summary of scientific and technical achievements by each.

John B. Southard - Project XIII

In the early part of the contract period, we completed our flume studies on sand waves, begun during an earlier contract period. From a series of 35 runs with medium to coarse sand in the large ONR-funded recirculating open channel, we studied the nature and behavior of dunelike bed forms in equilibrium with steady unidirectional currents for a wide range of sand sizes (0.4-0.8 mm) and current velocities. At low current velocities, the stability field for ripple bed configurations narrows with increasing sand size and pinches out at about 0.7 mm. At higher current velocities, dunes or megaripples are the stable bed configuration for all sand sizes studied. Dune configurations are divided into two groups: two-dimensional dunes, with fairly straight and regular crests and no localized scour in troughs, are formed at relatively low current velocities; and three-dimensional dunes, with discontinuous and irregular crests and strong localized scour pits in troughs, are formed at relatively high current velocities. A plot of flow depth vs. current velocity shows excellent agreement, in both geometry and hydraulics, between this picture of dunes in the flume runs and that of dunes or megaripples described by others in marine environments.

Also during the contract period, we made use of Seaflume, an instrument whose development was begun during the previous contract period. Seaflume is designed to be lowered from a surface ship to rest on a totally undisturbed sediment bed in the ocean. A controlled current can then be passed over the bed and the erosional response recorded photographically. This flume was first used by R. A. Young in a shallow estuarine environment in Buzzards Bay, Massachusetts. Threshold shear velocity for in-situ erosion of the muds ranged from 0.32 to 0.84 cm/sec there, corresponding to U_{100} values of about 8 to 15 cm/sec, apparently independent of time of year and bulk physical properties but dependent upon the state of the tide. Erosion was often but not always initiated at biogenically disturbed points on the bed. The same muds were also redeposited and bioturbated for 1 to 60 days in a large seawater recirculating channel in the laboratory. Mean threshold shear velocity decreased with bioturbation time in the flume but was greater by a factor of up to two than for muds eroded in situ, even for the longest bioturbation times. Studies of erosional threshold have been continued in deeper water in the Gulf of Maine. The later part of the contract period was devoted to thorough redesign of Seaflume to produce an instrument capable of free-fall deployment in the deep ocean.

John M. Edmond - Project XVII-A and XXIX

The geochemistry group under the supervision of Edmond has had responsibility for one major long term project on the chemistry, physics and biology of particulate matter in the oceans, and for two shorter term investigations - one on the chemistry of dissolved trace metals (1974-1977) and the other on the chemistry of the hot springs on the Galapagos Spreading Center (1978-1979).

The suspended material investigations centered around the large volume In Situ Filtration System developed on a previous contract by J.K.B. Bishop (Bishop and Edmond, J. Mar. Res., 34, 1, 1976). Initially this was used to collect material in profile from the upper 400 m of the water column. A later development enabled sampling to 1500 m. The 400 m profiles from the equatorial and south western Atlantic have been completely worked up (Bishop et al., Deep Sea Res., 24, 571, 1977; Bishop et al., Deep Sea Res., 25, 1121, 1978). A report on the first profile collected over the Galapagos Spreading Center in 1977 is in press (Bishop et al., Deep Sea Res., 1980), a second profile from the same location (1979) is close to completion as is the one collected in conjunction with the Honjo sediment trap experiment off Barbados (1979). Two profiles from the Panama Basin made in connection with the Sediment Trap Intercomparison Experiment (1979) are being worked on as is that from Santa Barbara Basin (1978) made with the MANOP trap intercomparison. These profiles have yielded unique information on the chemistry, biology, morphology and flux of suspended material in the upper ocean. Particularly valuable has been the information on large particles, fecal material, recovered in abundance from the large volumes filtered (up to 20 m^3).

An important and surprising outgrowth of this project was the successful foram culturing project (Ketten and Edmond, Nature 278, 546, 1979). Since the filtration system acts as an 'ideal' 1μ plankton net, all life stages of the foraminifera are represented in the samples. In an effort to reproduce these the organisms were cultured in the laboratory through first generation calcification for the first time.

The trace metal project built upon our successful work with barium, the first well determined trace metal in sea water (Bacon and Edmond, Earth Planet. Sci. Lett., 16, 66, 1972). We were subsequently able to report the first accurate data for copper (Boyle and Edmond, Nature, 253, 107, 1975), nickel (Sclater, Boyle and Edmond, Earth Planet. Sci. Lett., 31, 119, 1976) and cadmium (Boyle, Sclater and Edmond, Nature, 263, 42, 1976). Our methods have been implemented by a number of investigators and form the basis of the extensive work now being carried out nationally on trace

metal geochemistry in the oceans.

The work on ridge crest hydrothermal systems revolved around the followup to the 'discovery dives' in 1977. The Galapagos Spreading Center was visited again in April 1979 and several new fields discovered and sampled. A very extensive chemical investigation is now nearing completion with publication anticipated in mid-1980.

Based to a large degree on work supported by this Omnibus Proposal Edmond received the Macelwane Award of the American Geophysical Union in 1978.

John G. Sclater and Barry Parsons - Projects XVIII-A and XXVIII

During the first four years of the five year program, this project was devoted primarily to applying the theory of plate tectonics to the understanding of the morphology and magnetic signature of the sea floor. Within this time period, we sorted out the development of the Bouvet triple junction in the South Atlantic, the Indian Ocean triple junction and the tectonic history of the Philippine Sea. Further, Sclater, Parsons and Lawver have shown that in the North Atlantic there is a relation between free air gravity and residual elevation anomalies, and Parsons and Sclater have extended the empirical depth age relation for the entire history of the ocean floor and demonstrated how well the predictions of a simple plate model match the observations.

In the last two years, the program has concentrated on the correlation between gravity observations across the sea floor and convection in the upper mantle, and an understanding of the tectonic history of the Madagascar Ridge and the sea floor between this ridge and the Crozet Plateau. Whilst the latter study is still underway, the former has resulted in an interesting explanation of the exponential flattening of the depth of the ocean with increasing age.

Tanya Atwater - Project XVIII-B

In the study of a typical slowly spreading ridge, the mid-Atlantic ridge near 37°N, MacDonald, a graduate student in the WHOI-MIT Joint Program, found that most of the topography at the ridge is structurally controlled. This was observed through the Deep Tow examinations, sonar records and lava flow.

In the study of the oblique, slowly spreading Reykjanes Ridge, Atwater and Shih participated in a Deep Tow cruise and were able to determine the tectonic sequence of the Reykjanes ridge. Their analyses found that the surface expression, at least, appeared to be fault controlled, not volcanically controlled, as is generally assumed.

Working with MacDonald, Atwater was able to show from Deep Tow data on the mid-Atlantic ridge that the ridges and transform faults are unequivocally not perpendicular. Atwater, in an extensive study of rocks from the FAMOUS study found that the intensity of magnetism decreased abruptly with distance from the center and showed that most of the decay probably occurs in the first million years.

Along with MacDonald, Atwater was able to complete a worldwide survey of more ordinary mid-ocean ridge trends and their relationship to their transform fault trends.

Carl Wunsch - Projects XXI and XXII

To understand the smallest scales of motion in the ocean, Wunsch and Eriksen constructed a "microscale array" (MSA) to make measurements of the field of motion. For the first time, comparisons could be made between vertical velocity measured directly with current meters with its estimates from temperature sensors. Calculation of wave number - frequency spectra on smaller horizontal and vertical scales than has been possible before allowed them to begin to distinguish "waves" from diffusive or passive structures.

Eriksen (Ph.D. Thesis, 1976) produced a complete model of the internal wave and fine-structure fields near the high frequency cut-off. As part of INDEX, Wunsch set an array of seven moorings and five pressure gauges in the Indian Ocean for recovery in 1977.

Hendry and Wunsch completed (Hendry, 1975) a detailed examination of internal tide records in the western North Atlantic. They have shown that in the MODE-I region, the semi-diurnal tide was almost wholly in the fundamental mode and was phase stable, propagating away from the continental shelf to the northwest. Through re-examination of all site D records for both semi-diurnal and diurnal tides, Hendry has shown that the semi-diurnal tide is generated to the north at the continental shelf. The diurnal tide appears to be mainly barotropic and confined to the shelf region.

In a search to learn more about internal waves, Riser (M.S. Thesis, 1974) found a significant variation in the energy levels of the internal wave band from the rough to smooth area in the deep water of the MODE-I area. This was perhaps the first real indication that topography is a generator of internal waves. In the thermocline, Riser found that in the MODE-I area the internal wave energy levels appeared related to the overall structure of the mode "eddy".

Wunsch described the degree to which the deep water internal wave field could be characterized by a universal isotropic spectrum, and by using data from a carefully selected homogeneous set of deep water observations, found significant deviations from universal equilibrium only near a large seamount. Wunsch has seen that there are many places where the energy level is substantially and significantly above the universal open ocean value, and there is an indication of a weak relationship between energy level and anisotropy.

Wunsch, working with Walter Munk of Scripps, has developed a scheme for large scale ocean monitoring by acoustic means. They call the system "tomography" after the medical X-ray procedure which is analogous. Preliminary plans for experimental tests in the coming year have been completed. It is believed that the system may be the answer to the problem of how to monitor the ocean on large scales.

Wunsch has developed an analytical model of acoustic propagation in the ocean which permits a study of some of the qualitative features of SOFAR propagation. The model is useful as an analog for studying the inverse acoustic problem. It shows, in terms of sound channel parameters, such features as the Sofar cut-off burst, multiple rays with the same identifiers, and inversions of arrival time.

Eric Mollo-Christensen - Project XXV

After having explored and familiarized himself with sources of remote sensing information and learning how to utilize such data in computer analysis systems, Mollo-Christensen examined large volumes of satellite data, from all the available satellite data sources, looked for surface signs of oceanic dynamics, and tried to interpret such signs in a quantitative manner. In addition, he worked out theories for phenomena that seemed to be suggested by satellite imagery, without being able to verify, in all instances, that that was indeed the case, namely, that the

analyzed phenomenon was indeed present at the time and place of observation. Because of this, some of the phenomena analyzed have to be accepted merely as new theories. Among the processes examined have been: over-reflection of internal waves from a current, inspired by GATE observations; billows of front, inspired by GOES imagery; edgewaves along the shore, the presence of such waves being suggested in GOES images; and interpretation of internal wave packet spacings in terms of seasonal upper mixed layer heat storage. Several publications reported these analyses and interpretations.

Additionally, significant effort was devoted to formulating specifications for a satellite data system, and to planning for integrated utilization of remote sensing and in situ data. This resulted in a proposal which has been funded under the Selected Research Opportunities program by the Office of Naval Research. Progress in the research has been crucially dependent upon access to computer facilities for satellite data processing, and the help from the Center for Space Research and Engineering at the University of Wisconsin and the Air Force Geophysics Laboratory is gratefully acknowledged. Visits to NOAA/AMOLS and NOAA/EDIS have also been helpful, and the interesting exposure to data processing afforded by a visit to the Goddard Space Flight Center, NASA, should also be acknowledged.

The work is continuing with increased emphasis on computer modeling as an adjunct to remote sensing data interpretation, and stronger attention to nonlinear wave phenomena and wave processes in general. The first data from SEASAT synthetic aperture radar is showing promise in this respect, and the increased availability of aircraft radar data is also proving useful.

Stanley R. Hart - Project XXVI

Hart has completed a study of the variations of a series of trace elements and isotopes in a 500 meter section of ocean crust. Two new techniques for directly dating the duration of sea water circulation in the crust have been developed. One involves the Rb-Sr dating of alteration minerals such as smectite and celadonite. The other involves comparison of $^{87}Sr/^{86}Sr$ ratios in vein calcites with the known variation of seawater $^{87}Sr/^{86}Sr$ through time. The resulting ages show that circulation occurs dominantly during the first five million years after formation of the crust. Concentrations of K, Rb and Cs in the oceans are probably controlled by competing reactions involving the dissolution of new basaltic crust in seawater and the

precipitation of minerals such as smectite from seawater. The Sr/Ca ratios of vein calcites are considerably lower than those expected for precipitation from seawater, showing that the circulating solutions have gained Ca relative to Sr during interactions with the ocean crust. With these results, we are now able to model, to first order, the timing and chemical budget of seawater - ocean crust interactions.

Henry M. Stommel and Lloyd Regier - Project XXIX

A two-axis Doppler sonar ship's log was purchased from AMETEK/Straza Division and installed on the R/V GYRE of Texas A & M University. This instrument measures the Doppler shift of a short pulse of acoustic energy back-scattered from drifting plankton in order to determine the relative velocity between the water and the ship. The instrument was modified (in accordance with the suggestions of the manufacturer and Dr. Russ Davis of Scripps Institution of Oceanography) to allow vertical profiles of relative velocity to be made to a depth of 100 meters. By combining fixes of the ship's position obtained from LORAN-C with the relative velocity profiles, profiles of the current relative to the earth were obtained. The instrument was employed during the Local Dynamics Experiment of the POLYMODE program to obtain maps of the current structure in the upper 100 meters over a 200 kilometer by 100 kilometer area of the Sargasso Sea. This effort marked the first intensive use of this method to obtain such maps.

Over a period of 50 days, 5 maps of currents were obtained in the POLYMODE data. Although no definitive intercomparison was possible between the currents obtained with this method and currents measured by more conventional means, the acoustically determined currents were in rather close agreement with currents computed geostrophically from the observed density field, both with regard to magnitude and direction and with respect to the spatial structure of the current field. The ageostrophic component of the current field bore no simple relationship to the observed winds and perhaps was dominated by inertial currents. In general, the currents were observed to be uniform (within a few cm/second) from 20 meters depth to 100 meters, and there was no evidence of an Ekman flow. The power of the acoustic method lies in the fact that velocity profiles can be made in near real-time from a ship steaming at full speed.

Sean C. Solomon - Project XXX

Solomon's funding, which began on 1 June 1978, was for participation in the OBS calibration test at Lopez Island in June 1978, for participation in the Rivera Ocean Seismic Experiment (ROSE) during January-March 1979, and for several analysis tasks on the ROSE data. The purpose of ROSE has been to study with a large network of ocean bottom seismometers the structure and evolution of young oceanic lithosphere and the earthquake tectonics of the Orozco fracture zone. The field program was successful, with full recovery of all MIT instruments and about 90 percent recovery of all OBS's involved.

Our earliest analysis efforts on the ROSE data have been from the second leg earthquake and explosion records. A preliminary location of all earthquake sources large enough to have been recorded by at least four stations has been completed, based on arrival time data from most of the ROSE network, and a joint paper describing this data set is currently being prepared. An early report of this work, and of the tectonic interpretation for the Orozco transform area, was given by Anne Tréhu at the Fall AGU meeting. She will continue her analysis of the ROSE earthquake data as a major part of her Ph.D. thesis. Analysis of the explosion records from the first leg for purposes of characterizing seismic wave energy partitioning and transmission efficiency is also underway as of the close of the contract period.

Giselher Güst - Project XXXII

A paper on performance and specifications of metal-clad hot wires in oceanic environments was written, submitted and accepted by JGR, with minor revisions. (This paper is presently being withheld until the company corrects some discovered engineering flaws in the deep sea configuration).

Two deep-sea capsules with turbulence sensors and micro-processed, digital fast recorders were built and successfully deployed jointly with the benthic acoustic current meter system of Sandy Williams. Data sampled at 32 Hz/channel on velocities, Reynolds stress and bottom stress at heights less than 5 cm above the sea bed were recovered from depths 62m, 1000m, and 5000m. The quality of some data-channels proved to be noisy due to water absorption in the probe shaft-sealing. (Since its discovery, the company has been working to solve this problem and is close to success). A computer-compatible data processing chain is now being set up.

Charles C. Eriksen - Project XXXIII

Eriksen analyzed INDEX mooring data from the Indian Ocean and found a spectrum of equatorial waves (internal gravity, mixed Rossby-gravity, and Kelvin modes) with a wavenumber bandwidth as broad as for the mid-latitude internal gravity waves models of Garrett and Munk. The model spectrum reproduces spectral features in the data characteristic of equatorial waves, including energy ratios and coherences. It predicts the emergence of inertial peaks from monotonic spectra at low latitudes; these peaks have larger "blue-shifts" than mid-latitude theory predicts, consistent with the data. The observations suggest an increase in internal wave energy across the tides when the inertial frequency is subtidal.

Other moored arrays have been set in equatorial regions, one in the Indian Ocean and one in the Pacific Ocean. These are intended to extend our knowledge of equatorial wave phenomena to low frequencies as well as relate equatorial motions to mid-latitude phenomena.

Edward A. Boyle - Project XXXIV

Boyle has collected and analyzed a suite of surface water samples for copper. Copper concentrations off Northwest Africa (non-upwelling) are higher than those from the Atlantic upwelling zone. Concentrations in the Panama Basin are higher than either.

These initial observations are consistent with a model for the distribution of copper in the surface waters of the ocean with the following features: (1) Copper is introduced to coastal waters by diffusion from continental shelf sediments, and then (2) mixes horizontally by advection and diffusion into the interior of the ocean, and then (3) is removed by biological scavenging into the deep sea, where it is partially regenerated.

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